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In conclusion, we have experimentally demonstrated a novel double-clad fiber laser incorporating a polarization beam splitter and polarization switch. We also believe that we can add more amplifying sections, and in this way, couple more pump light into the cavity to produce high power, diffraction limited output. This should be particularly effective with PM large mode area double clad fiber.

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A New Yb-doped double-clad fiber laser cavity Using Polarization Switching Technique

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We report on a new design for a fiber laser cavity in which it is possible to utilize multiple independent pumps. We demonstrate the feasibility of this novel technique by building a laser with output power close to 30W, which is only limited by the pump sources available to us.

1. Introduction

Efficient, high power single mode fiber lasers have been rigorously sought after for applications that range from material processing to military applications. In the late eighties, it became clear that scaling to higher output power was limited by the pumps themselves. The fiber group at Polaroid invented the double-clad fiber as a brightness converter, which enabled the use of high power multimode semiconductor pumps to generate diffraction limited fiber laser output. Over the past several years, breakthroughs in specialty fiber fabrication and novel pump coupling schemes have led to single mode fiber lasers ranging from several hundred Watts and approaching 1 kW with nearly single transverse mode beam quality [1] [2] [3]. At the moment, there are two major pumping techniques which can be classified as side-pumping and end-pumping. Among side pumping schemes, L. Goldberg, (U.S. Patent 5854865), has proposed a 90° V-shaped groove cut into the outer and inner claddings of the fiber; T. Manzur, (U.S. Patent no. IPN WO 00/54377) has proposed a coupling window with refractive index higher than that of the fiber's core was formed on one side of the fiber cladding by physically removing a portion of the cladding material; IPG Photonics uses fiber fused side couplers. In Japan, a group of researchers are also working on an unusual side pumping technique, which is called a structure-type (disk) fiber laser [4]. End pumping of a fiber laser is always most convenient and efficient, especially if fiber splices with Bragg gratings can replace bulk mirrors. The disadvantage of end pumping, however, is that a fiber has but two ends. In the following, we will demonstrate how a polarization switching technique may be used to create multiple fiber ends, and allows the radiation to pass twice through each amplifying section for more efficient energy extraction. We believe that this technique combined with polarization-maintaining (PM) fiber laser sections can be used to achieve high power.

2. Design Principle

The technique uses a polarizing beam splitter combined with polarization switching in each arm of the cavity to define a "super cavity" with multiple gain sections that can be end pumped. This technique was first realized for a Nd:YAG laser system [4][5]. In that earlier effort, a multi-rod resonator with 6.8W output and a slope efficiency of 52% were attained. In the following, instead of using laser rods, we use polarization-maintaining double-clad rare-earth-doped fiber with slightly multi-mode core as the gain sections.

Figure 1a shows the schematic diagram of our experimental setup. A 1/4 wave plate is used to convert P polarization to circular polarization, that, upon reflection and passing a second time through the 1/4 wave plate, becomes S polarization. The photon path for laser photons is shown in figure 1b and may be described as follows. Signal photons with left-circular polarization that are reflected from the output coupler will go through _ wave plate and become P photons. They will then pass through PBS and be coupled into the lower amplifier section. After passing through the end-pumped fiber, the signal photons will be amplified and switched to S photons.

Upon passing a second time through the PBS, they will be reflected and coupled into right hand side fiber amplifier section. When these S photons pass through the amplifier section and are reflected, they become P photons that are coupled into the amplifying section on the left. They are then amplified, pass through the _ wave plate, are reflected, and, upon passing through the 1/4 wave plate a second time, they become S photons which are amplified again and sent to the output coupler. This arrangement guarantees that the output will be circularly polarized. The signal photons make two passes through each amplifying section, which enhances the efficient of energy extraction.

3. Experiment

The three pumps are pigtailed laser diodes systems operating at 915nm with 60W combined maximum pump power. The Yttrium Vanadate polarization beam splitter has over 99% transmission and at least 40dB extinction ratio. The PM double-clad fiber is octagon-shaped with the widest dimension 250 μm, made by Nufurn. A low-index polymer coating forms the second cladding and provides a NA of 0.45. The single-mode core has a diameter of 30 μm with a NA of 0.06. To maximize the coupling ratio and minimize unwanted back reflection, all fiber ends are angle cleaved. The 1/4 wave plate as well as the aspheric lenses were AR coated at 1.1 μm. Even with the aspheric lens, the best fiber-fiber coupling efficiency achieved was about 93%. We believe that with AR coating at the fiber end, the coupling efficiency can be further improved. The absorption coefficient at 915nm was measured at 2.54dB/m. The background loss was measured to be ~10dB/km for the multimode propagation at 915nm and ~0.22dB/m for the laser radiation at 1080nm in the core. Zero degree dichroic mirrors with over 99.5% reflection at 1080nm and ~85% transmission at 915nm were used as high reflectors. A 10% broadband mirror was also used as the output coupler.

We have developed a program for numerical simulation using standard rate equations. Our initial assumption was that the Yb-doped fiber was a quasi-four level system and we obtained a set of coupled partial differential equations. These were solved numerically [6] [7] [8] [9] by applying appropriate boundary conditions. To evaluate the accuracy of the simulation tool, we ran several experimental tests. Figure 2 shows the simulation result of a simple fiber laser cavity, which is composed of above mentioned PM-YDDF, high reflector and a 4% output coupler (Fresnel reflection). According to the simulation, the optimum fiber length should be 5.2 meters with ~76% conversion efficiency. The experimental result, shown in figure 3, was in very good agreement with that assessment.

Using our simulation tool, we found that the optimal section length of the "super cavity" should be 3.4 m [Fig. 4], with a ~59% conversion efficiency. Figure 4b shows the signal power distributions throughout the three amplifying sections and the numbers correspond to the same path through each amplifier section in figure 1b. In our simulation, 12W of pump power at 915nm was injected into the lower amplifying section, 18W into the right section and 20W into the left section. This uneven pump distribution agrees with the actual available pump power out of the three pump systems. The center lasing wavelength was 1080nm and all three amplifying sections consisted of 3.5m active fiber through each gain section. According to the simulation result shown in figure 4a, the residual (unabsorbed) power was about 11% of total injected pump power, which was twice that of the simple cavity in figure 2a.

The experimental results obtained with this new cavity design are shown in figure 5. The fiber spool had a diameter of 15cm. The maximum conversion efficiency measured was ~55% with 27.5W output power at 1080nm and the threshold was about 1.6W. As shown in figure 5b, the slope efficiency slightly declined when output power exceeded 22W. The beam quality M^2 was measured around 2.2. We believed that the performance of bulk optics suffered at high power, which led to higher coupling losses in the cavity. The maximum slope efficiency was measured to be 62%. There was a small discrepancy between the theoretical and experimental results, which

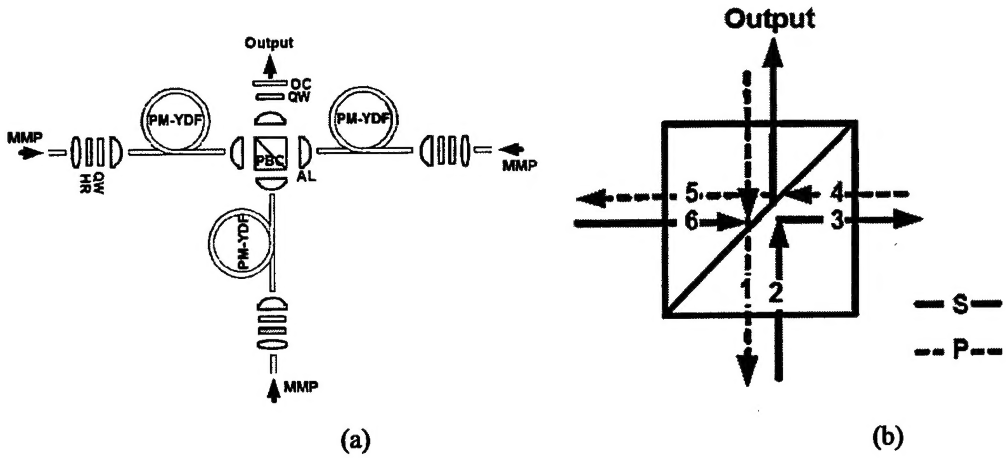

Figure 1. Schematic diagram of the fiber laser cavity setup a) AL: aspheric lens. TFP: thin film polarization beam splitter. QWP: zero order _ wave plate. DCYF: double-clad Yb-doped fiber. SMF: single mode fiber. FBG: fiber Bragg grating. OC: output coupler; b) radiation paths

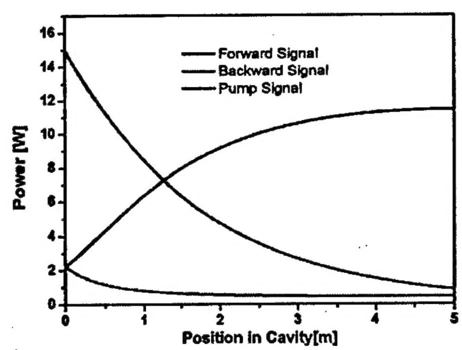

Figure 2. (a) Schematic laser radiation beam paths throughout the cavity. (b) Simulated pump and laser radiations power distribution inside the cavity.

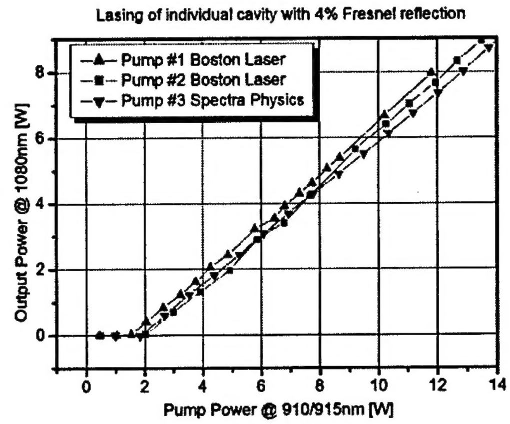

Figure 3. (a) Ouput power and conversion efficiency at 1098nm as a function of the launched pump power for three Nufern "legs" of combiner

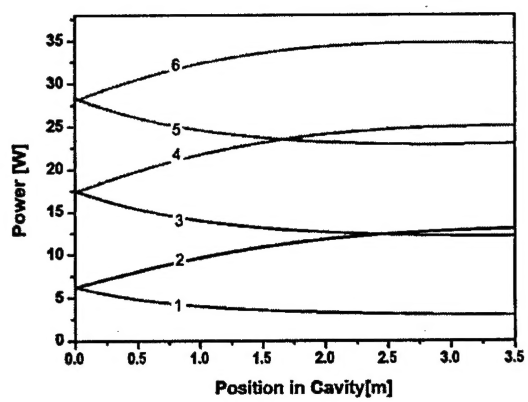

Figure 4. Power distribution along cavity path

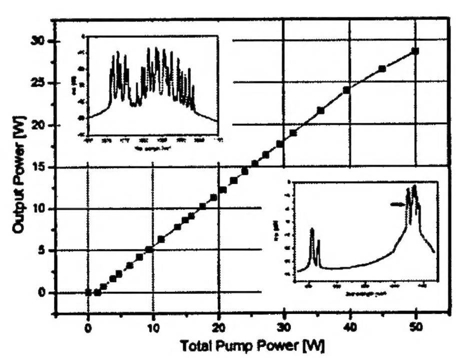

Figure 5. Output power of laser combiner, spectral distribution

might be due to higher than expected cavity loss. The relatively low conversion efficiency for the "super cavity", when compared with the simple laser cavity, was mainly due to the accumulated fiber-fiber coupling loss (currently ~7%/pass) in the cavity and relatively high residual pump power. Simulation shows that if coupling loss would be reduced to 2%/pass, the conversion efficiency could be improved to 65%.

4. Conclusion

In conclusion, we have experimentally demonstrated a novel double-clad fiber laser incorporating a polarization beam splitter and polarization switch. We also believe that we can add more amplifying sections, and in this way, couple more pump light into the cavity to produce high power, diffraction limited output. This should be particularly effective with PM large mode area double clad fiber.

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Figures